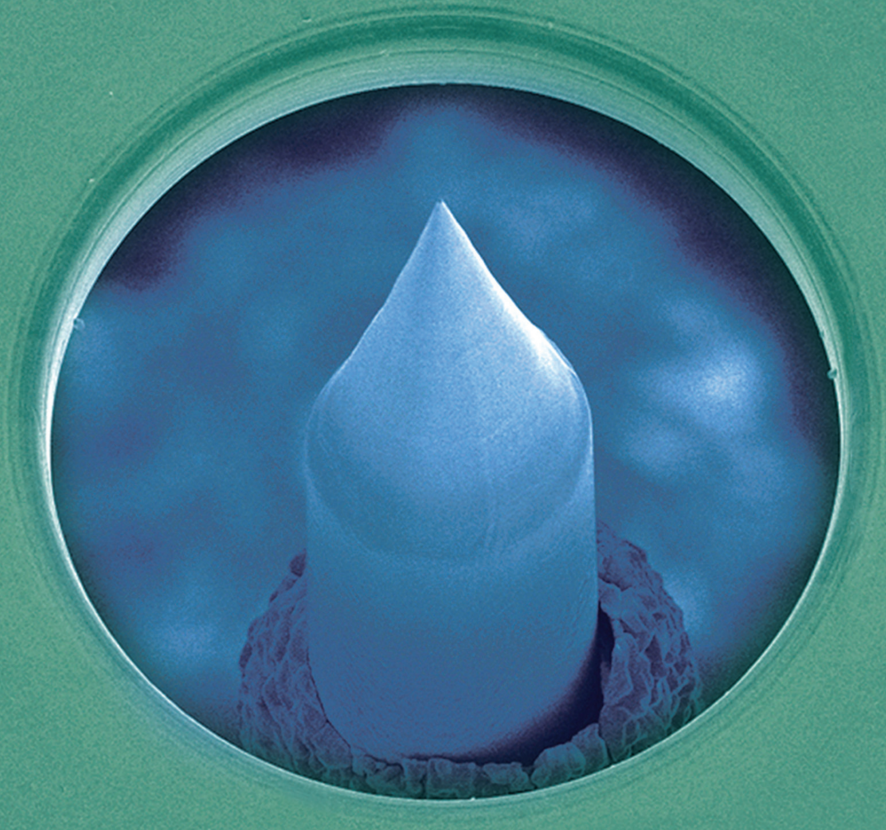
Physics of Schottky Electron Sources

Theory and Optimum Operation

Merijn Bronsgeest



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Preface

The Schottky electron source is the predominant emitter type in focused electron beam equipment, but although used extensively and satisfactorily, its properties are not fully understood. New developments and increasingly more stringent performance requirements ask for a better understanding: What is the best possible performance from a Schottky source for a given application? Which operating parameters are associated with that performance, and how stable is this “best” performance? These are the questions addressed in this book.

The content for this book is the result of my work as a PhD candidate in the research group Charged Particle Optics at Delft University of Technology in the Netherlands, and it is my pleasure to acknowledge the interaction with Greg Schwind, Lyn Swanson, Sean Kellogg, and Alan Bahm of FEI Beamtech in Hillsboro, Oregon, USA, throughout the years; the technical assistance of Jan de Looff, Frans Berwald, and Jacques Nonhebel of the research group Charged Particle Optics in Delft and of Ted Tessner of FEI Company; the opportunity given to me by Mike Lysaght and Greg Schwind of FEI Company to work with the sources research team of FEI Company in Hillsboro in May–July 2006; the courtesy of FEI Company for the use of some of its scanning electron microscopy (SEM) images in this book; the contributions to the work on practical brightness by the late Jim Barth of the research group Charged Particle Optics in Delft; and the support and guidance of my doctoral advisor Pieter Kruit, without whom this book would not exist.

Merijn Bronsgeest

Introduction

Electron beams are used for many applications. The most well-known example is probably the old-fashioned cathode ray tube (CRT) television, which changed our daily life. And an important step for science and technology was the invention of the electron microscope. Today's focused electron beam equipment uses electron beams mainly for imaging purposes, elemental characterization, and writing.

With respect to imaging or chemical analysis, electron irradiation of a sample produces a wealth of different signals for detection, each with specific information on the sample, for example:

- elastically back-scattered electrons;
- secondary electrons (ejected from the sample by inelastic scattering interactions with the beam electrons);
- Auger electrons (a beam electron removes an electron from the core of an atom, leaving a vacancy, an electron from a higher energy level falls into the vacancy, and the energy that is released is transferred to another electron, which is ejected from the atom with a characteristic kinetic energy);
- characteristic X-rays (a beam electron removes an electron from the core of an atom, leaving a vacancy, an electron from a higher energy level falls into the vacancy, and the energy that is released is transferred to a photon);
- light (a beam electron promotes an electron from the valence band to the conduction band (semiconductor sample), leaving a hole, and the electron recombines with a hole and emits a photon); and
- whether the sample is thin enough: transmitted electrons, which can be analyzed on changes in amplitude, phase, and/or energy with respect to the primary beam.

“Writing” with electrons is used, for example, to:

- locally functionalize a surface;
- create a charge pattern on the surface (for nanoxerography);
- locally expose a so-called “resist” layer on the surface (maskless lithography); and
- selectively deposit (part of) a precursor gas (electron beam–induced deposition [EBID]) (resistless nanolithography).

Crucial to any application is the electron source. The predominant emitter type in today’s focused electron beam equipment, and the topic of this book, is the so-called Zr/O/W{100} Schottky electron source.

Schottky electron sources are used in many different systems of different companies (e.g., FEI Company*, Jeol Ltd., Hitachi Ltd., Carl Zeiss, KLA-Tencor Corporation, Tescan s.r.o., Phi [Physical Electronics Inc.], RIBER, Applied Materials). To name a few examples: the Titan (scanning) transmission electron microscope (FEI Company), the Nova NanoSEM scanning electron microscope (FEI Company), the JBX-6300FS Electron Beam Lithography System (Jeol), the SU-70 scanning electron microscope (Hitachi), the JXA-8500F Electron Probe Micro Analyzer (Jeol), the Mira II CS scanning electron microscope (Tecsan), the PHI 700 Scanning Auger Nanoprobe (Physical Electronics), and the microscopes with the Gemini column (Carl Zeiss).

Each of the applications puts its own specific demands on the properties of the irradiation. To give two examples, in electron energy loss spectroscopy (EELS) material-specific information is obtained by measuring the loss in energy of the primary beam electron upon transmission through the sample, and the primary beam electrons thus preferably all have exactly the same energy, while for high-resolution imaging it is desirable to be able to focus the electron beam down to a very small spot on the sample with still enough primary electrons in it to generate a detectable signal within a reasonable amount of time. The latter requires a high reduced brightness of the beam.

Over the past decades the Schottky source has been used as an electron emitter extensively and satisfactorily. Its properties, however, are not fully understood, and the ongoing quest for ever

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higher resolution and throughput, in combination with the advances made in the quality of electron optical systems (e.g., aberration correctors), put an increasing demand on the performance of the source with respect to, for example, brightness, energy spread, and geometrical stability. Examples are the recent interest in multibeam and multisource systems (Zhang & Kruit, 2007; Dokania *et al.*, 2008), the TEAM project (Dahmen *et al.*, 2009), and the Magellan^{TM} (Young, 2009).

Such developments require better knowledge of the relation between the operating parameters of the source and the properties of the beam at the sample, and the stability of the physical shape of the emitter. These are the topics addressed in this book.

The Schottky source is typically operated in a vacuum environment of $\sim 10^{-9}$ mbar, and the electron emission is generated by heating the source and applying an electric field to it. Figure i.1 gives images of the Schottky emitter at different length scales.

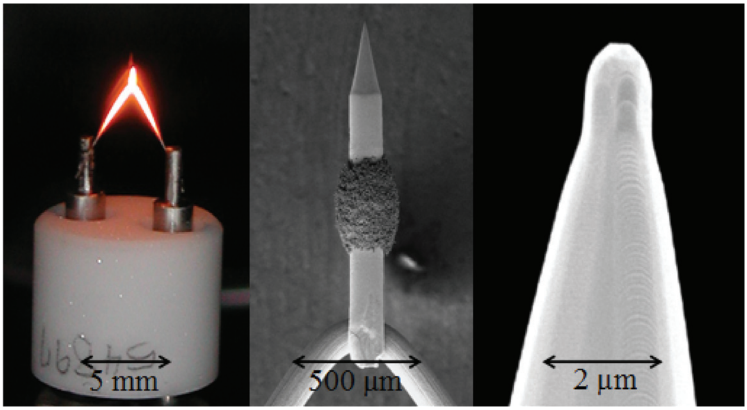

Figure i.1 Schottky emitters at different length scales.

The emitter consists of a single-crystalline tungsten wire, about 1 mm long and 125 μm in diameter. One end of the wire is etched down to a tip with a diameter of about 1 μm. Halfway along the wire a reservoir of ZrO_x is attached, and at the other end the wire is spot-welded to a polycrystalline tungsten loop. This loop is fixed to two poles, which are embedded in a cylindrical ceramic base 1 cm in diameter. By running 2.0–2.5 A of current through the loop the emitter is heated through resistive heating and thermal conduction.

At a standard operating temperature of 1,800 K the emitter and part of the tungsten loop are glowing brightly.

The electric field is applied by biasing the emitter negatively with respect to an extractor: a metallic plate or cone, with a central aperture, usually at about 0.5 mm distance from the emitter tip. The potential difference between the emitter and the extractor is typically a few kilovolts. In the standard configuration the emitter is operated with an extractor and a suppressor.

The suppressor is a metal cap with a small hole. The emitter protrudes from the suppressor cap through the aperture for about 0.25 mm. It can be seen just peeking out from the cap in Fig. i.2. In operation the suppressor is biased negatively with respect to the emitter up to a few hundred volts to suppress unwanted electron emission from the part of the emitter that is inside the cap.

Figure i.2 Schottky emitter with and without a suppressor cap.

Two examples of a suppressor-emitter-extractor module are shown in Fig. i.3.

Characteristic for the Schottky emitter is the low work function of the planes with the {100} orientation. This is caused by the presence of zirconium and oxygen on the surface, which reduces the work function of the {100} planes considerably with respect to other crystallographic orientations. Zirconium and oxygen are present in the reservoir on the base of the emitter, and at a high operating temperature they can reach the {100} planes through diffusion.

The most important {100} plane is the facet on the tip end (Fig. i.1). This facet delivers the electrons that will end up in the final beam for applications. Most of the emission from a Schottky source is not used: the total emission from a Schottky emitter is typically up to a few hundred microamperes. The emission from the end facet is typically a few tens of microamperes. The beam current that is used in applications is cut out from the facet beam and typically contains of the order of a few picoamperes up to maybe microamperes.

Figure i.3 Examples of integrated source-suppressor-extractor modules (left: YPS AES-170 module; right: Denka TFE module).

The Schottky source has been studied by several investigators. In total about 50 articles have been published. Swanson *et al.* have done a great deal of the pioneering work from the late sixties to the mideighties in the area of Portland, Oregon. This area is still a location of active research: it is where FEI Company has concentrated its emitter research and development efforts. FEI Company is one of the few manufacturers of Schottky emitters (others are Denka and York Probe Sources Ltd.).

The first patent on the Schottky source was filed in 1964 as a result of the research in Oregon. Since then, about 15 US patents have been awarded, mainly to FEI Company (Oregon), Hitachi Ltd. (Tokyo), and Denka (Tokyo), although three early patents are from Wolfe, who worked for General Electric Company (New York) and Burroughs Corporation (Detroit).

During the work for this book there have been many discussions with FEI Company.

The structure of this book is as follows: in the first part of this book beam properties are addressed. Chapter 1 gives the electron emission theory that is used throughout this book to quantify the properties of emission from a surface. Chapter 2 addresses how the input parameters for emission theory relate to the practical case of a Schottky emitter in operation. In Chapter 3 we zoom in onto the emission from the end facet and how that arrives at the extractor, and in Chapter 4 we make the connection between facet emission and the final beam properties relevant to applications.

The second part, Chapter 5, is dedicated to the geometrical stability of the shape and consequences for the properties of the beam.

Finally, in the last part, Chapter 6, the focus is on achieving and maintaining maximum performance from the source for different applications.

The Schottky effect, the lowering of the potential barrier at the surface by applying a field to it, plays an important role in the emission properties of the Schottky electron source (Fig. i.4).

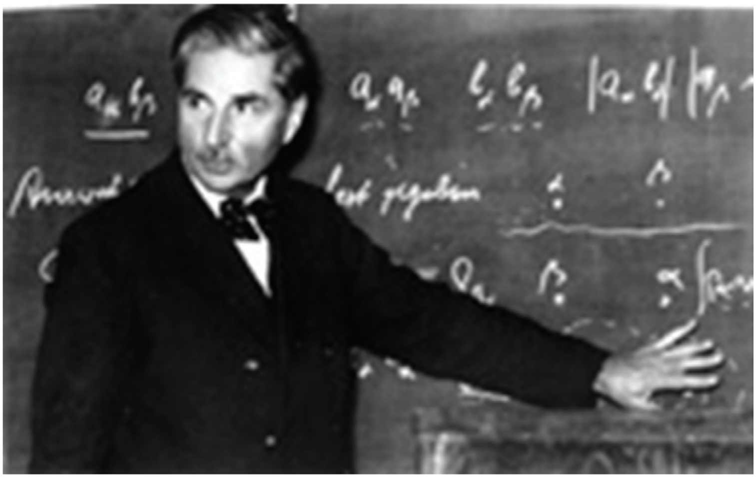

Figure i.4 Walter Hermann Schottky (1886–1976).